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A case study of multi-seam coal mine entry stability analysis with strength reduction method

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Abstract

In this paper, the advantage of using numerical models with the strength reduction method (SRM) to evaluate entry stability in complex multiple-seam conditions is demonstrated. A coal mine under variable topography from the Central Appalachian region is used as a case study. At this mine, unexpected roof conditions were encountered during development below previously mined panels. Stress mapping and observation of ground conditions were used to quantify the success of entry support systems in three room-and-pillar panels. Numerical model analyses were initially conducted to estimate the stresses induced by the multiple-seam mining at the locations of the affected entries. The SRM was used to quantify the stability factor of the supported roof of the entries at selected locations. The SRM-calculated stability factors were compared with observations made during the site visits, and the results demonstrate that the SRM adequately identifies the unexpected roof conditions in this complex case. It is concluded that the SRM can be used to effectively evaluate the likely success of roof supports and the stability condition of entries in coal mines.

Keywords

Coal mine ground control; Multiple seam mining; Phase 2; FLAC3D; Strength reduction method; Roof supports

1. Introduction

Since the introduction of roof bolts in the coal mines during the late 1940s and 1950s, roof bolts promised to dramatically reduce roof fall accidents [1]. However, ground falls still remain a significant factor in underground coal mine injuries and fatalities. In 2013, ground

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falls accounted for 4 of the 14 fatalities and 166 of the 1577 reported lost-time injuries in underground coal mines.

The design of appropriate support systems requires the understanding of: (1) the variable nature of the rock mass, (2) the performance and characteristics of the roof support, (3) the interaction between the rock mass and the installed support system, and (4) the in-situ and mine-induced stress distribution around the excavation. Over the past 25 years, multiple design approaches have been used in coal mine ground control. The approaches include empirical mechanistic methods, empirical statistical analysis, rules of thumb, and numerical methods [2]. In the U.S., Analysis of Roof Bolt Systems (ARBS) can be given as an example of an empirical method. ARBS uses relatively simple equations to calculate the intensity of support provided by a roof bolt system and compare it with a suggested ARBS value [3]. The suggested ARBS design equation is derived from an analysis of 100 case histories. The ARBS design equation is dependent on two parameters: depth of cover and Coal Mine Roof Rating (CMRR). More recently, a probabilistic design approach was developed by Canbulat and van der Merwe in South Africa [4]. In this method, the variability of the rock mass, the mining geometry, and support characteristics are included in the analytical models. The major advantages of these two methods are: (1) they can be applied rapidly and easily, (2) complex rock mass/roof support interaction mechanisms are represented with simple equations, and (3) they are supported by large databases. However, both methods generally ignore mining-induced stress distribution, details of the roof support system, details of the geological setting, and the interaction between the support system and the rock mass.

To evaluate such complex interactions during support design, numerical models can be used. In general, experience-based design backed by empirical and analytical methods have found more application in the industry than numerical methods. The preference for empirically based methods may be related to the difficulty of selecting appropriate input parameters and interpreting success or failure when using numerical models. Recently, procedures were developed by Esterhuizen et al. to address these two concerns related to modeling [5,6].

2. Entry stability analysis with the strength reduction method (SRM)

The strength reduction modeling technique has a long history in numerical model analysis in rock slope stability engineering [7]. This modeling technique was adapted to underground coal mine entry analyses by Esterhuizen [8] to address the need for a method to compare the effectiveness of different support systems when designing ground control support in coal mines. The focus of the method is on large stress-driven roof falls that extend more than 1.00 m above the entry roof line. The SRM calculates a stability factor of the entry roof by gradually reducing the rock strength until failure is indicated. The stability factor is expressed as the inverse of the strength reduction factor. For example, if collapse occurs when the strength is reduced by a factor of 0.5, the entry stability factor will be 2.0.

Esterhuizen et al. [5] also developed an approach to systematically derive initial input parameters for modeling coal-measured rocks based on the field methods used in the Coal Mine Roof Rating (CMRR). Sedimentary rocks can contain weak bedding structures that have a significant impact on their stability. Anisotropic rock strength in the numerical models is achieved by user-defined functions.

The numerical models for determining the SRM stability factors are created using the FLAC3D finite difference code. Details of the model layout and input selection are described in Esterhuizen et al. [5]. Model calibration and validation studies were conducted to ensure that the developed modeling technique provides realistic estimates of the stability of mine entries. As part of the validation studies, model-calculated stability factors were compared to the results of the empirically based ARBS method [3]. Outcomes of the validation studies are presented by Esterhuizen et al. [6,9].

3. Case study

In this paper, the stability of the entries in a multiple-seam mine in central Appalachia is evaluated with the strength reduction method. The case study mine had unexpected stress-related ground conditions due to topography and multiple-seam effects [10]. Stress mapping and observation of ground conditions were used to quantify the success of entry support systems in the affected areas. In this paper, the SRM-calculated SF values are compared with the field observations.

3.1. Mining and geotechnical parameters at the case study mine

The Darby Fork No. 1 Mine is operated by Lone Mountain Processing, Inc., and is located in Harlan County, KY. The mine produces bituminous coal from the Darby and Kellioka coal beds by the retreat room-and-pillar mining method. In this paper, performances of the Nos. 1 and 5 entries in the L-6, L-5, and L-4 panels along the cross section A–A' in the Kellioka seam are evaluated with the SRM (Fig. 1).

The workings on the Kellioka coal bed are accessed from the Darby coal bed by a set of three slopes which connect to the L-7 Right panel. The Kellioka, Darby, and previously mined Owl panels have been stacked vertically so that the panel edges and barrier pillars between panels are superimposed. The depth of cover varies between 90 and 610 m, and the thickness of interburden between the Kellioka and the Darby coal beds varies between 9 and 15 m. In the Kellioka, the L-7 panel was developed first to provide access from the Darby coal bed. The operator developed and retreat-mined the L-8 and L-9 panels to the east followed by the L-6, L-5, and L-4 panels to the west. The L-7 panel was mined in a northward direction, and the L-8, L-9, L-6, L-5, and L-4 panels were mined southward. Pillars in the L-7 panel were not extracted to provide access to the remainder of the Kellioka workings and to provide intake ventilation.

The production pillars are designed to 24 m × 24 m centers with 70° crosscuts. Panel width is 98 m, with slab cuts of 9 m taken on both sides of the panel during retreat mining. Entries and crosscuts are mined at 5–5.5 m wide. The mining height varies between 1.8 m and 2.1 m, while the coal bed thickness varies around 0.9–1.2 m. Details about the case study mine are published by Tulu et al. [10].

3.2. Unexpected stress-related damage in the case study mine

During development of the L-6 panel, advancing to the south (Fig. 1), unexpectedly the No. 5 entry (western) experienced symptoms of stress-related damage, while the other four entries and the cross cuts were unaffected. The roof damage in the No. 5 entry appeared to be classic horizontal stress-related damage with the formation of roof cutters along the length of the entry [10]. The cutters were mostly located along the eastern corner or along the center of the No. 5 entry. Some floor heave occurred near the center of the entry. The conditions in the No. 5 entry deteriorated to such an extent that it became necessary to install timber cribs to support the roof. Roof cutters and poor conditions continued to be experienced as the L-6 panel development advanced towards the south, with an improvement in roof conditions towards the end of the panel, after crosscut 41. The stress-related damage observed in the No. 5 entry of the L-6 panel was unexpected because the No. 1 entry was expected to be subject to horizontal stress-related damage, as shown in Fig. 2. The No. 5 entry was actually expected to be in a favorable situation because it was supposed to be in a zone of relieved horizontal stress.

In an attempt to explain the occurrence of the failure in the No. 5 entry of the L-6 panel, two-dimensional finite element stress analyses were conducted [10]. The stress analysis models included the effects of the initial horizontal stress, the effect of the variable topography on vertical stress, and the details of the mined panels and entry development. The results indicated that the unusual stress damage was most likely related to the effect of the mountainous topography, which produced a rotated stress field at the location of the current workings. The rotated stress resulted in asymmetrical interactions between the upper and lower workings, explaining the baffling damage observations [10]. To remedy the situation, the No. 5 entry in the subsequent panels was developed 9 m to the east of the planned position, to locate it away from the topography-affected stress. This change in layout has been successfully applied in the L-4 and L-5 panels and has improved conditions compared to the experience in the L-6 panel.

4. Field observations

The L-6, L-5, and L-4 panels were visited by OMSHR personnel on several occasions as the panels were developed. The following observations were made:

(1) There was not any notable damage on the Nos. 2, 3, and 4 entries of each panel. This shows that vertical stress on the Kellioka seam was relived successfully by stacking Kellioka panels vertically with the previously mined Darby and Owls seams.

(2) The No. 5 entry of the L-6 panel experienced stress-related damage, while the No. 1 entry and the cross-cuts were unaffected. Initially it was considered that the roof damage in the No. 5 entry was classic horizontal stress-related damage with the formation of the roof cutters along the entry (Fig. 3).

(3) The damage to the No. 5 entry appears to have been caused by asymmetrical loading of the rock by the mountain slope to the west of the L-6 panel [10]. For the L-5 panel, the No. 5 entry was shifted 9 m to the east. Conditions in the No.

5 entry of this panel were noticeably improved compared to those of the L-6 panel (Fig. 4).

(4) The No. 5 entry of the L-4 panel was also shifted 9 m to the east. During development, the No. 5 entry of the L-4 panel performed better than L-6. The operator tried to develop the entry 9 m to the west (of its original planned position) on two occasions. During both of these step-outs, the entry started to show stress-related damage and the entry development was swung back to the 9 m shifted position. When the operator started to retreat-mine the pillars, the No. 5 entry started to deteriorate (Fig. 5). During the site visit, it was also observed that the roof shale matrix had fossils and coal sparse structures.

5. Evaluation of topography and multi-seam mining-induced stress

One of the input parameters for the SRM is the stress distribution around the entry before it is excavated. In order to determine the total stress distribution induced by in-situ and multiple-seam stresses, the Phase 2 numerical model that was previously used by Tulu et al. [10] was updated to improve the estimate of the horizontal stress due to tectonic loading and the depth across all panels at the Darby Fork No. 1 Mine. The analysis was conducted by modeling different sections across the panels, capturing the topographic effect of the mountains and a stream valley. The model simulated vertical stress due to gravity, and the tectonic stress was modeled with the locked-in stress option in the Phase 2 model. The updated model results in in-situ horizontal stresses and *K*-ratios that are consistent with expectations based on stress measurements in the Appalachian coal region [11]. Table 1 shows that those in-situ horizontal to vertical stress ratios calculated manually (expected) and computed with the Phase 2 model are very close to each other.

The multi-seam effect caused by the full extraction of the panels in the overlying Darby and Owl coal beds was modeled prior to entry development on the Kellioka. The gob in the Owl and Darby panels was modeled as a soft material that attracted loads similar to what would be predicted by an abutment angle of 21°. The elastic modulus of each gob is calibrated separately to give the expected 21° abutment angle loading. Heights of the gobs in the Owl and Darby panels were selected as 4.5 m and 6.0 m based on the experience of the mine. Fig. 6 shows the overall model layout and surface topography modeled.

6. Calculation of entry stability with the strength reduction method

6.1. Principal stresses

The average major and minor principal stresses at the proposed location of each of the entries in the Kellioka seam were queried from the Phase 2 model and are presented in Table 2. The Phase 2 model results showed that direction of the major principal stress was almost horizontal at all the entry locations. Therefore, in the SRM model, the major principal stress was defined to be horizontal and the minor principal stress vertical.

6.2. Rock mass strength

The immediate roof of the Kellioka seam workings is described as dark grey shale with sandstone streaks. Along the Kellioka panels the roof and floor lithology changes. It is possible to have shale with siderite bands, fossils, or coal spars. In these cases, the unit rating will be lower than the expected rating. In the FLAC3D SRM model, the roof and floor of the Kellioka seam is modeled as a shale rock with matrix and ubiquitous joint properties derived from the parameters listed in Table 3, based on the procedure described by Esterhuizen et al. [6]. During the L-4 panel site visit, shale with fossils and coal sparse were observed along the No. 5 entry roof. In order to account for different anisotropic strength factors, two set of parameters were used (Table 3).

6.3. Entry support system

The basic support in the panels consists of four fully grouted 1.82 m long No. 6 torque-tension bolts in a row. Row spacing is 1.22 m. The fully grouted bolts are installed through a strap. Supplementary support is two 3.66 m long super-bolts (75 grade 22.2 mm) installed every other row. In the SRM, the same bolting pattern was modeled (Fig. 7).

7. SRM results and comparison with the field observations

Table 4 shows the summary of the SRM entry stabilities. During the analysis, shale rock with lower anisotropy factor was used to model the roof of the No. 5 entry of the L-4 panel. From the field observations, it is known that conditions in the No. 1 entry of all the panels were satisfactory. Also, the No. 5 entry (which is shifted 9 m to the east) of the L-5 panel was satisfactory. The No. 5 entry of the L-6 panel experienced excessive stress damage and floor heave. The operator installed supplementary supports (cribs) to keep this entry open. During the development stage, the shifted No. 5 entries of the L-4 panel were in relatively good condition compared to the No. 5 entry of the L-6 panel, but during retreat the No. 5 entry conditions started to deteriorate. Again, the operator installed supplementary support along the No. 5 entry of the L-5 panel (both shifted and in its original position) to keep it open.

When shale roof with a unit rating of 59 is used in the SRM models, it is found that the stability factor reduces to 1.24, indicating potential damage around the entry No. 5 of the L-6 panel. The No. 1 entry stability factor of the L-6 panel (1.59) is 28% higher than that of the No. 5 entry. The stability factors of No. 1 and No. 5 entries of the L-5 panel are 17% and 23% higher than the No. 5 entry of L-6. The stability factor of the No. 5 entry of the L-4 panel, when it is not shifted to the east, shows potential stress damage. The stability factor for this entry is 1.96 when it is shifted 9 m to the east. This final result contradicts with the field observations. During the field observations, it was also noted that roof of this entry might have a lower unit rating of 48. When the SRM models were run with the shale roof unit rating of 48, the stability factor of this entry dropped to 0.85 for the not-shifted case and 1.24 for the shifted case. Both of these values indicate potential instability of the entry roof.

During the site visits, it was observed that severe roof damage in the No. 5 entry of the L-6 and L-4 panels was accompanied with floor heave (Fig. 5 – in background behind fall rubble). The SRM model results also show that floor heave and roof collapse are linked (Fig. 8). Prior to collapse of the roof, a relatively large deformation takes place in the roof with only minor deformation in the floor (Fig. 8a). When the roof starts to collapse, excessive floor heave also takes place (Fig. 8b). In the SRM models, collapse occurs when failure extends above the bolts. During the collapse, stress within the roof is relieved and transferred to the upper layers, ribs, and floor. This stress re-distribution appears to initiate the floor heave. This mechanism might explain the reason for observing stress damage in the roof with associated floor heave in the No. 5 entry of both the L-6 and L-4 panels.

8. Conclusions

In this paper, it is shown that the SRM can successfully predict the stability of an entry even in a mine with complex multiple-seam interactions. Operators can use the SRM to identify potential roof stability problem areas and develop solutions to these problems before mining.

In complex stress situations, such as the multiple-seam interactions described in this paper, the mining-induced stress can be derived from global stress models.

Based on core log data and stress information, several SRM models with different bolting patterns can be evaluated. It is also possible to include the variability of the rock mass, the mining geometry, and support characteristics in the SRM models.

The SRM models provide useful insight into likely roof stability conditions; however, they should only be used as an assessment tool to assist in the design and engineering analysis of proposed support systems.

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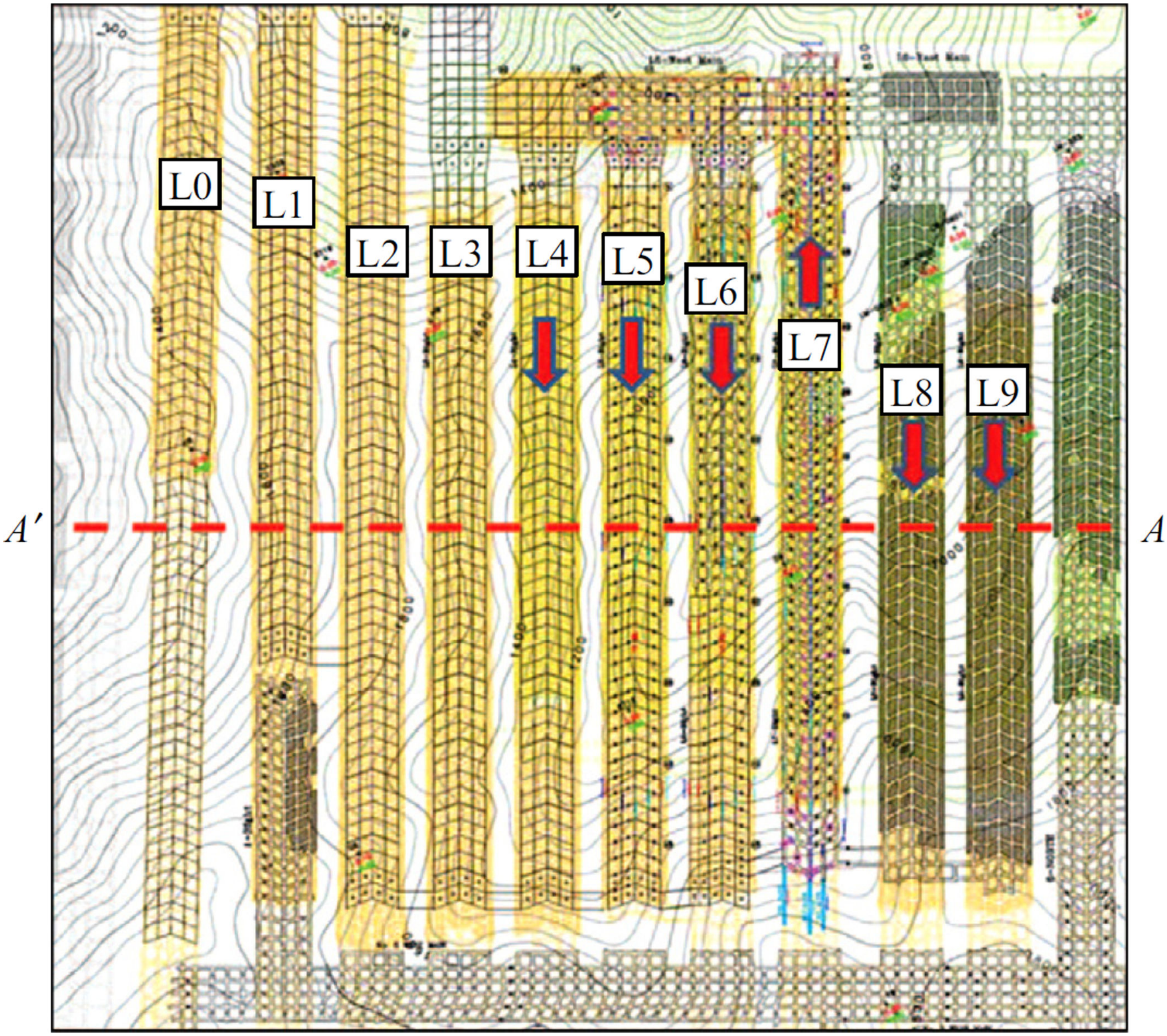

Fig. 1.
General layout of the panels in the area of interest.

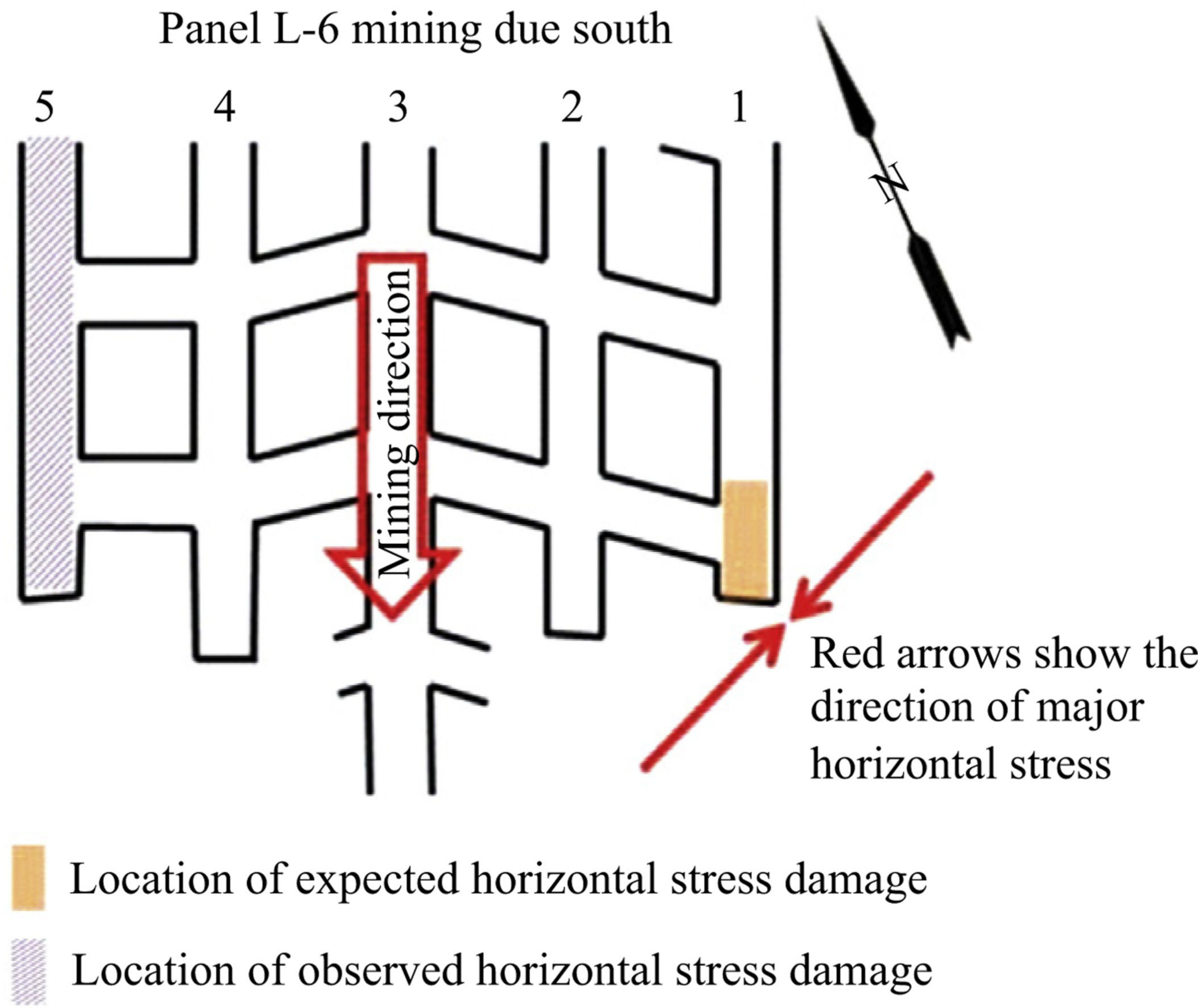

Fig. 2.

Sketch showing the expected and observed location of horizontal stress damage.

Fig. 3.
Roof cutter damage in the No. 5 entry of the L-6 panel.

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Fig. 4.

Typical conditions in entry No. 5 of the L-5 panel at a location where the entry was shifted 9 m to the east.

Fig. 5.

Roof damage and floor heave at No. 5 entry of the L-4 panel at location where entry was stepped out by 9 m.

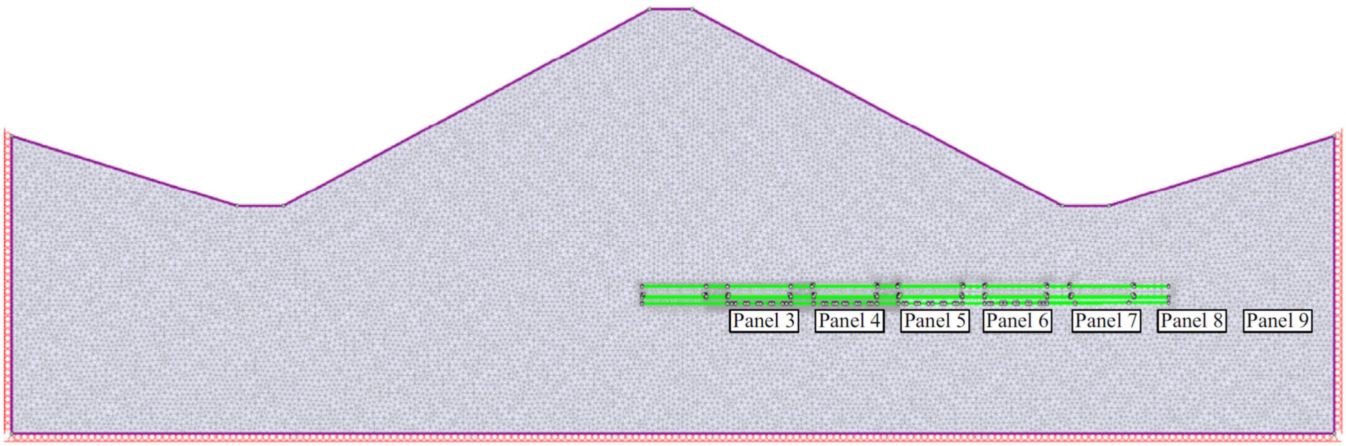

Fig. 6.
Phase 2 model geometry.

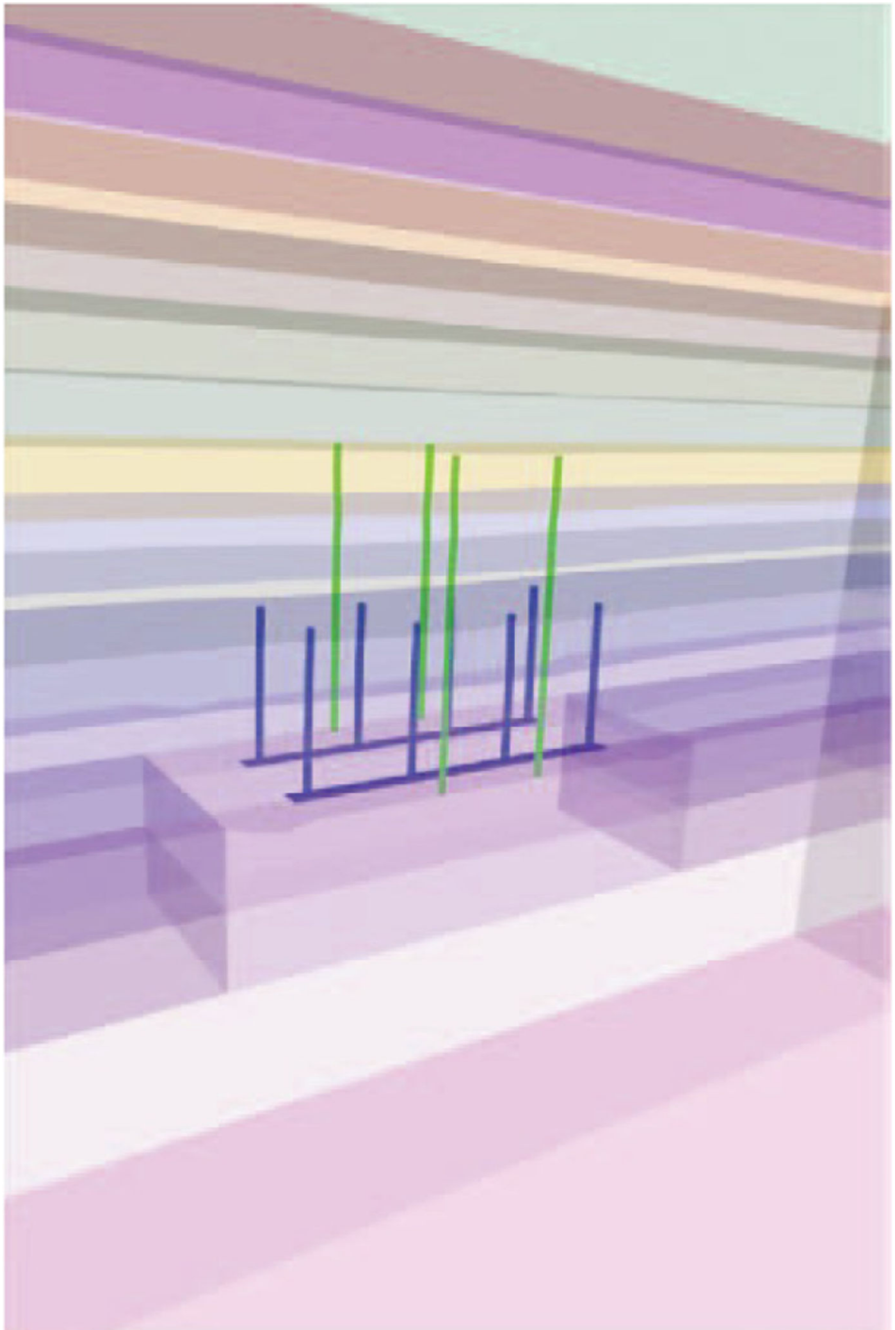

Fig. 7.
Bolting pattern modelled in FLAC3D for the SRM analysis.

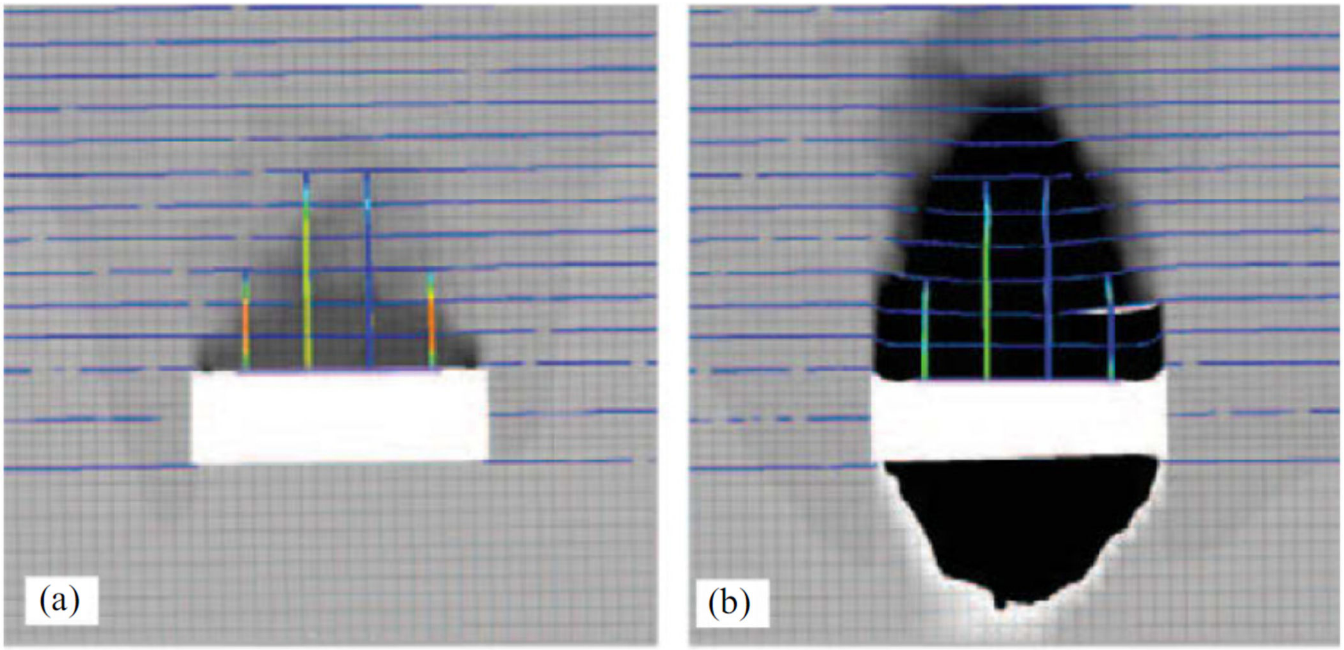

Fig. 8.
Displacement on the roof before collapse, floor is stable (a) and floor heave occurs after roof collapse (b).

Table 1

Expected and model calculated horizontal/vertical stress ratios at the L-6, L-5, and L-4 panels prior to mining.

Panel number	Average depth (m)	Vertical stress (MPa)[a]	Expected horizontal stress			Expected *K* ratio	Phase 2 *K* ratio
			Poisson's effect (MPa)	Tectonic stress (MPa)[b]	Total (MPa)		
6	233	5.94	2.55	6.52	9.07	1.53	1.48
5	321	8.18	3.52	6.52	10.04	1.23	1.22
4	408	10.40	4.47	6.52	10.99	1.06	0.97

Elastic modulus of the Kellioka roof shale = 13.03 GPa.

[a] Unit weight of the overburden is 25.5 kN/m^3.

[b] Low stress Central Appalachian tectonic strain = 5.0×10^{-4} [11].

Table 2

Major and minor principal stresses calculated from Phase 2 model.

Panel	Entry	Sigma 1 (MPa)	Sigma 3 (MPa)
6	1 (Not shifted)	11.88	3.99
	5 (Not shifted)	14.27	4.22
5	1 (Not shifted)	12.31	3.50
	5 (Shifted 9 m)	11.49	3.16
4	1 (Not shifted)	12.16	2.80
	5 (Not shifted)	14.46	2.70
	5 (Shifted 9 m)	10.07	2.49

Table 3

CMRR parameters used to derive input parameters for FLAC3D model.

Roof Shale	UCS (MPa)	Bedding strength rating	Bedding intensity rating	Unit rating
Strong	40	25	20	59
Weak	40	22	12	48

Table 4

SRM entry stability results.

Panel	Entry	Field observation	SRM entry stability factor
6	1 (Not shifted)	Minor roof damage and floor heave	1.59[a]
	5 (Not shifted)	Moderate roof damage. Roof bolter experienced difficulties during the development stage. Supplementary supports required to keep the entry open	1.24[a]
5	1 (Not shifted)	Minor roof damage and floor heave	1.45[a]
	5 (Shifted 9 m)	Minor roof damage and floor heave	1.52[a]
4	1 (Not shifted)	Minor roof damage and floor heave	1.45[a]
	5 (Not shifted)	Moderate roof damage when entry was stepped out to the not-shifted position. Supplementary supports required to keep the entry open	1.24[a] (0.85)[b]
	5 (Shifted 9 m)	Initially minor roof damage. Supplementary supports required to keep the entry open when retreat mining.	1.96[a] (1.24)[b]

[a]Unit rating of the roof is 59.

[b]Unit rating of the roof is 48.